Seismic Protection Of Domed Structures

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Abstract

Domes represent a major visual statement either glorifying God, or celebrating an event, or announcing the power of Government. Many domed buildings have been built in areas of severe seismicity, putting them at risk. The structural response of domes is complex, and protecting domes from earthquakes by conventional strengthening methods is not always reliable. Seismic isolation protection of domed structures is practicable and feasible and is illustrated in this paper with five examples in the United States: two completed projects (San Francisco City Hall and Oakland City Hall, both in California), one project in design (Pasadena City Hall, California*),* and two feasibility studies (Utah State Capitol and the Old Courthouse in St. Louis, Missouri). The performance criteria and corresponding analysis are presented, together with engineering details and construction issues. Seismic isolation represents a significant preservation and protection technology for domed structures.

Introduction

There are numerous buildings in the inventory of recognized historic buildings in the United States which are crowned with monumental domes. Most such buildings are civic structures housing important governmental functions. The majority of these buildings were built in the late 19th century and early 20th century. As such, seismic loads were not implicitly taken into account in their design. Considering that a large percentage of these buildings were built in areas of moderate to high seismicity, their vulnerability during seismic events is unquestionable, and their retrofit is a challenge.

These historic domed structures are typically massive structures with large inertial mass. Their dynamic response is complex and at times difficult to predict because of: a) the complexity of the structural systems, b) the combination of different materials used in their construction, c) the archaic materials with lesser known properties, and d) the limitations of available analytical tools. While the domes may possess adequate strength because of their inherent shape, the dome support structures (the drums) usually lack the strength, stiffness, ductility and load path continuity to safely withstand seismic loads. Further, they greatly amplify forces imparted to the dome structures. These buildings are typically constructed of non-ductile archaic materials with degrading hysteretic properties, which are often the cause for major damage and perhaps instabilities. In addition, the buildings are blessed with highly ornate and decorative non-structural elements which give them. their distinguished character, but pose a significant shortcoming for seismic response, by creating the potential for major or falling hazards.

To address such shortcomings in the context of a historic structure is not a small challenge. Conventional retrofit solutions, while addressing some of the response issues, do not fully address the unique dynamic characteristics of domed structures and the amplification of seismic forces at the dome level. Further, the new lateral resisting elements must be compatible in stiffness with the initially very stiff existing archaic materials

Figure 1 San Francisco City Hall

such as unreinforced brick masonry (URM), hollow clay tile (HCT), granite, etc. In order to achieve this deformation compatibility in fixed base structures, with potentially large deformations, extensive lateral resisting elements must be added which compromise the historical and functional integrity of these buildings. Therefore, alternative retrofit solutions must be considered. Base isolation has proven to be a very effective technology in seismic retrofit and preservation of historic domed structures. In the following pages, base isolation concepts for five such buildings are discussed. The retrofit strategy for San Francisco City Hall is discussed in detail, while others are briefly described.

San Francisco City Hall

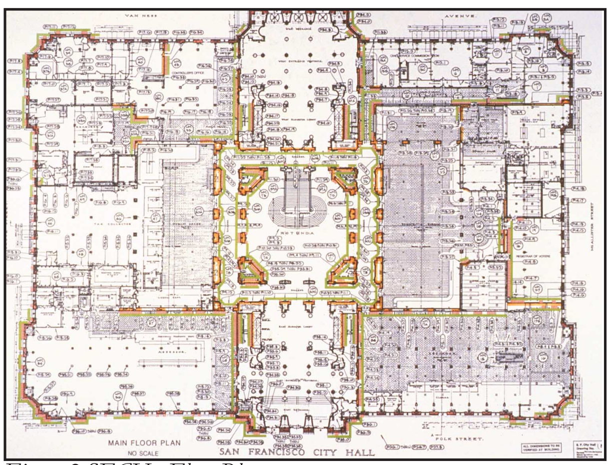


Figure 2 SFCH - Floor Plan

The San Francisco City Hall (SFCH) is a monumental building located in the San Francisco Civic Center Historic District, and is recognized as one of the most notable examples of classic architecture in the United States. The building was designed in 1912 to replace the City Hall building that was destroyed in the 1906 San Francisco Earthquake.

The building was damaged in the 1989 Loma Prieta Earthquake, which resulted in the need for repair and seismic strengthening. Several seismic retrofit schemes were considered. A base isolation scheme was selected as the most appropriate scheme; one which best responds to the performance criteria, the functional needs and the need to preserve the historic fabric of this building, while being the most cost effective solution.

The five story SFCH building (Figure l) with its rectangular plan has plan dimensions of approximately 309 feet by 408 feet. The dome with its lantern rises approximately 300 feet above the ground floor. The grand rotunda area in the center of the building is approximately 90 feet in diameter. On either side of the rotunda there are two large rectangular light courts which are open above the second floor (Figure 2). The rotunda and the light court openings create major diaphragm discontinuities which contribute to the existing

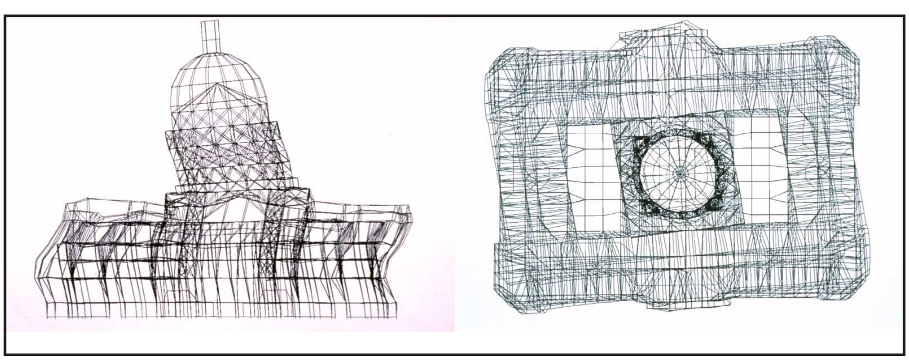


Figure 3 Existing Building Response

building's undesirable dynamic behavior (Figure 3). The building structure is composed of a complete steel frame with concrete slabs. The foundation system is shallow spread footings. The exterior granite walls are backed with URM. Many of the infill partition walls are constructed with HCT. The dome with its drum base is a multi-tiered steel structure supported on four steel columns Located at the four corners of the rotunda. The lateral load resisting system of SFCH is composed of three major components: the URM walls, the HCT infill walls, and the steel frame. The URM and HCT walls are the most rigid elements and provide the first line of seismic resistance. The steel framing is flexible and has minimal contribution to the lateral load resisting capacity of the building (Figure 4). There are numerous discontinuities and flexible zones in the building structure which impact its response to seismic loads. The Main floor is a flexible story because of discontinuity of some major brick walls at this level. In addition, the dome drum and its octagonal base are very flexible and highly amplify the force imparted to the dome structure. The flexible zone at the main floor and at the dome drum contribute to the unique response of this building to seismic forces (Figure 5) and govern the retrofit solution.

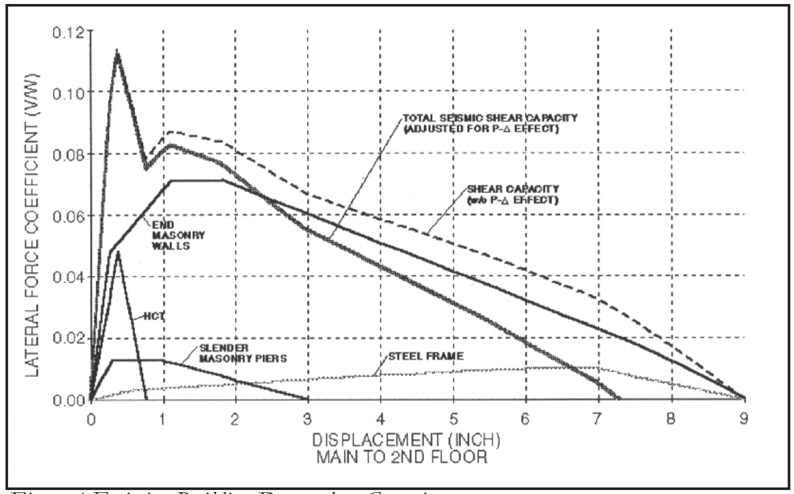


Figure 4 Existing Building Demand vs Capacity

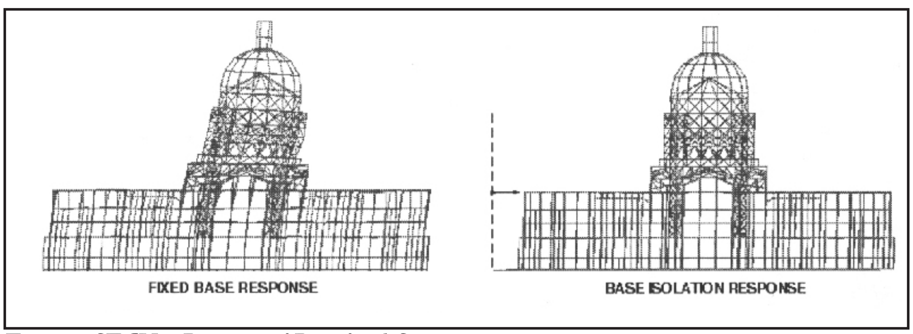


Figure 5 SFCH - Response of Retrofitted Structure

The analysis and design of the retrofit scheme for this complex building was an engineering challenge beyond the framework of conventional solutions. The analysis involved creating several analytical computer models of the building and performing a series of parametric studies to take into account the variations in configuration and in the material properties, etc. A comprehensive in-situ material testing program was conducted to better understand and account for properties of the archaic materials. Of the retrofit schemes which were studied, the fixed base schemes responded poorly to the dome seismic response, thus requiring dismantling of the dome cladding and major strengthening and rebuilding. This was not cost effective- and did not respect the preservation goals for this highly regarded historic building. Base isolation, on the other hand, not only reduces the overall building response, it greatly reduces the amplification of forces at the dome level by allowing essentially a rigid body movement of the structure above the isolation level (Figure 6). This proved to be a major benefit in the retrofit of SFCH, both in terms of improving the seismic response and in terms of savings in retrofit cost. In addition, base isolation reduced the story drifts substantially, thus making it more tolerable by the brittle structural and nonstructural historic elements. Although base isolation substantially reduces the seismic force that the building will experience, some lateral resisting elements were required to stiffen and strengthen the superstructure. New concrete shear walls around the two existing light courts, as well as new steel bracing at the dome and drum levels were added to provide the required lateral resistance. The base

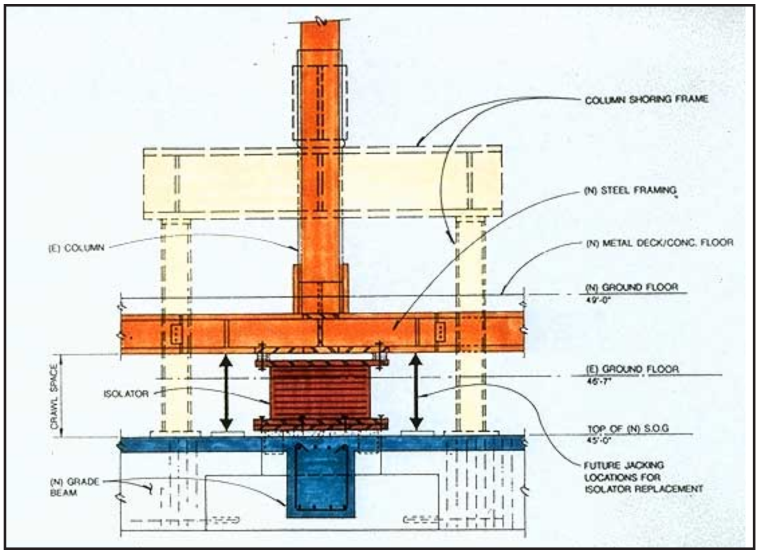


Figure 6 SFCH - Isolation System Assembly

isolation solution for SFCH involved installation of isolators above the existing foundations at the base of all columns and the URM walls. The existing foundations were enhanced by a system of new continuous grade beams. A new ground floor was created above the isolators to uniformly distribute the lateral forces to isolators.

The construction of this seismic retrofit scheme was extremely complex, and required special sequencing of the work. The potential vulnerability of the building during construction was given serious consideration, as the construction involved jacking and partial removal of 500 columns and nearly 1400 linear feet of massive brick walls at their base, in order to install the isolators. (Figure 6) shows the concept for jacking of a typical interior column (Figure 7) shows isolators installed in the basement.

The site conditions as well as the existing structure's dynamic characteristics made base isolation a viable solution for seismic retrofit of this monumental building. The construction of SFCH was completed in 1998.

Figure 7 SFCH - Isolators Installed

Oakland City Hall

The Oakland City Hall (OCH) was designed and constructed between 1910 to 1914. Repair and strengthening of the OCH was triggered by the 1989 Loma Prieta Earthquake, which resulted in severe damage and evacuation of the building. The building is comprised of a Podium containing a three-story Central Rotunda, and a ten-story base which is crowned by a distinctive and highly decorative 90-foot tall clock tower, rising 324 feet (Figure 8). The base structure is 124 x 184 feet in plan, and has a full basement level. The building has a complete steel frame. The steel frame is infilled by either unreinforced brick masonry (URM), unreinforced concrete (URC) or hollow clay tile (HCT) walls. The foundation system is a reinforced concrete mat over the entire basement area. The floors and roofs are constructed of reinforced concrete slabs supported on the structural steel frame. The exterior walls of the building are composed of URM faced with granite and terra cotta ornamentation.

While OCH is not a domed structure, its clock tower has dynamic characteristics very much like a dome drum structure. During the Loma Prieta Earthquake, the entire clock tower racked and shifted at its base resulting in an offset of 1 inch.

Figure 8 Oakland City Hall

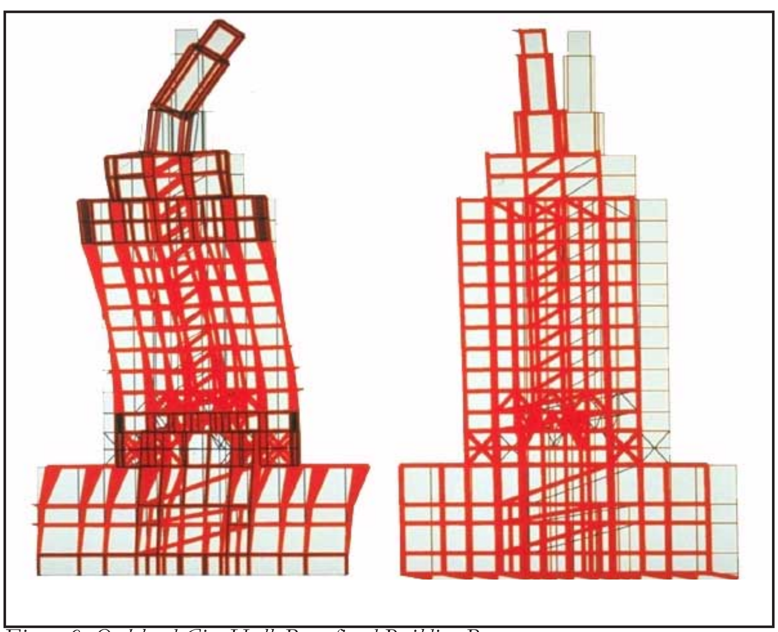


Figure 9 Oakland City Hall, Retrofitted Building Response

While fixed base retrofit schemes were studied, it was acknowledged that with conventional retrofit systems, the dynamic characteristics of the clock tower cannot be altered significantly without extensive and thus visually intrusive strengthening. Therefore, seismic isolation was considered. The base isolation scheme proved to be the most efficient, preservation-oriented and cost-effective strategy for the retrofit of OCH, because it not only reduced the seismic force level at the base of the building, it also altered the dynamic response and the deformed shape of the structure, thus reducing the required level of strengthening (Figure 9). The 112 isolators for OCH are installed at two different levels as shown in Figure 10).

The superstructure strengthening is composed of reinforced concrete structural walls, eccentrically braced steel frames, and concentrically braced steel frames at various levels of the building. Construction of OCH was completed in 1995.

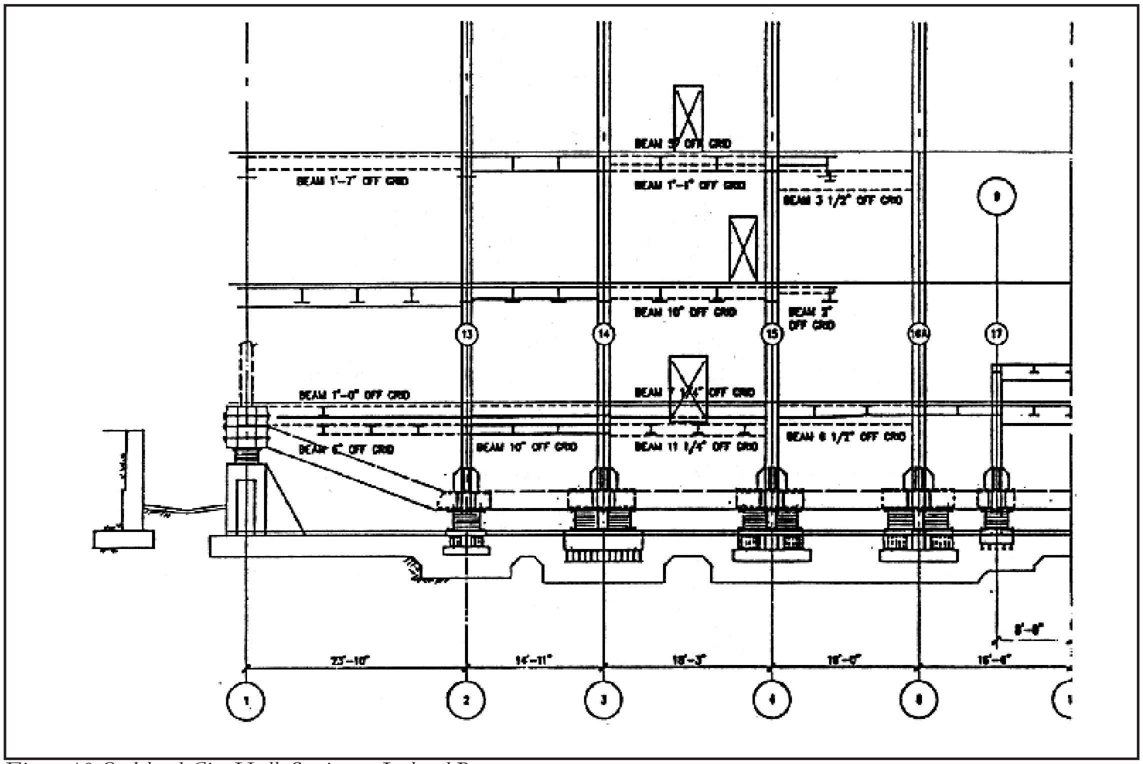


Figure 10 Oakland City Hall, Section at Isolated Basement

Pasadena City Hall

Figure 11 Pasadena City Hall

The Pasadena City Hall (PCH) is a monumental civic structure built in 1927. The overall building is basically "U" shaped in plan surrounding a landscaped courtyard and fountain. The building is composed of several major elements: a massive tower structure topped with a dome and cupola, rising 200 feet from the ground floor, two shaped office wings, and large stair towers located at the four corners of the courtyard. The east side of the courtyard is bounded by a one story arcade that links the ends of the office wings. The overall plan dimensions are 260 feet x 350 feet (Figure 11). The building, including the dome, is generally of cast-in-place concrete with some structural steel framing in the dome tower. The existing lateral resisting system includes a mix of concrete walls, piers and frames. Lateral resistance of the dome tower is provided by several elements.

The performance of the PCH building during a major earthquake with a 475 year return period was evaluated and is expected to be poor. The expected damage includes severe cracking and localized crushing of perimeter walls throughout the building, potential loss of vertical support at various discontinuities; cracking of the dome upper floor diaphragms and potential loss of vertical support for the diaphragms located between the dome tower and the supporting walls.

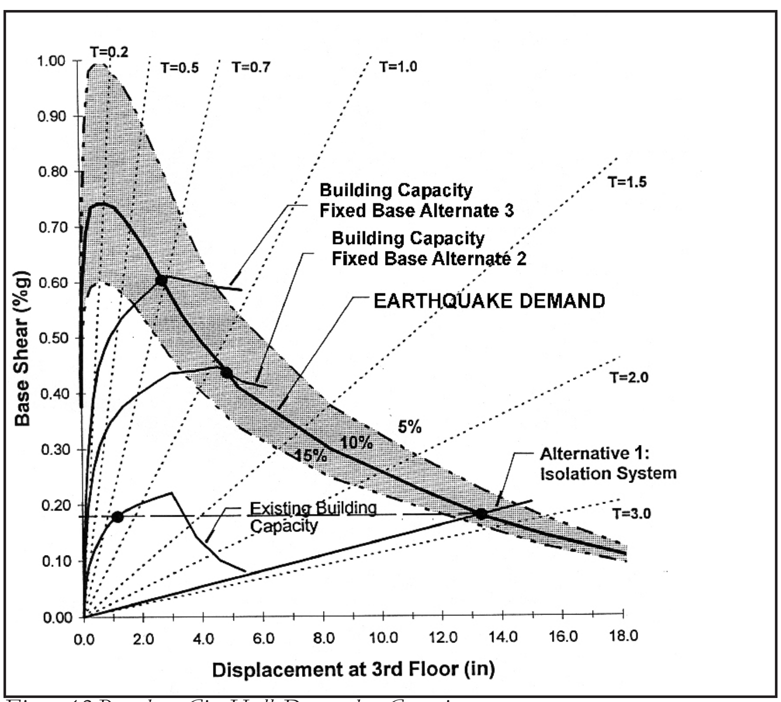


Figure 12 Pasadena City Hall, Demand vs Capacity

Three levels of desired seismic performance were established, and various retrofit schemes were studied to respond to those performance objectives. The three levels were: Life Safety, Limited Disruption, and Continued Function. Fixed base retrofit schemes as well as base isolation were considered. Base isolation was the only scheme that responded effectively to the Continued Function objective. Use of base isolation reduced the demand on the existing elements to a degree that no major strengthening of the superstructure is required except for creating load paths where existing discontinuities exist. (Figure 12) shows the response of existing and retrofitted building both fixed base and base isolated.

The base isolation scheme involves installation of isolators at the bases of all columns and walls at the basement level directly above the foundations allowing sufficient headroom for fill use of the basement. (Figure 13) shows the concept for isolator installation.

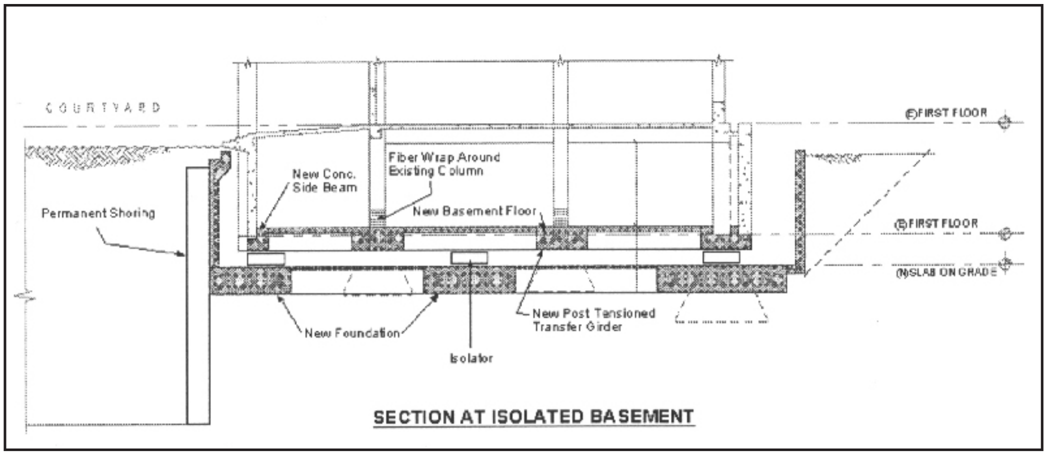


Figure 13 Pasadena City Hall, Section at Isolated Basement

Utah State Capitol

A technical feasibility study of base isolation seismic retrofit of the Utah State Capitol (USC) was performed in conjunction with Reaveley Associates in Salt Lake City. The USC was built in 1912 and is on the National Register of Historic structures in the United States. The building has plan dimensions of 215 feet x 403 feet, and is four stories tall with a full basement founded on shallow spread footings. The magnificent dome rises 180 feet above the ground (Figure 14). The existing structural system consists of reinforced concrete walls and columns and one-way joist and beam systems at floors. The building is clad with massive granite facade backed by unreinforced brick or hollow clay tiles. The dome structure, including the cylindrical base, is reinforced concrete faced with terra cotta.

Figure 14 Utah State Capitol

The existing structure, while massive, lacks the strength and the ductility to safely resist seismic forces from a major event. The cylindrical base of the dome has large openings which create discontinuities and major reduction in stiffness. Installation of an isolation system permits a reduced level of strengthening consistent with the historic preservation goals for this project. Isolators are envisioned to be installed at the top of the basement below the first floor. (Figure 15) shows the conceptual details of the base isolation system.

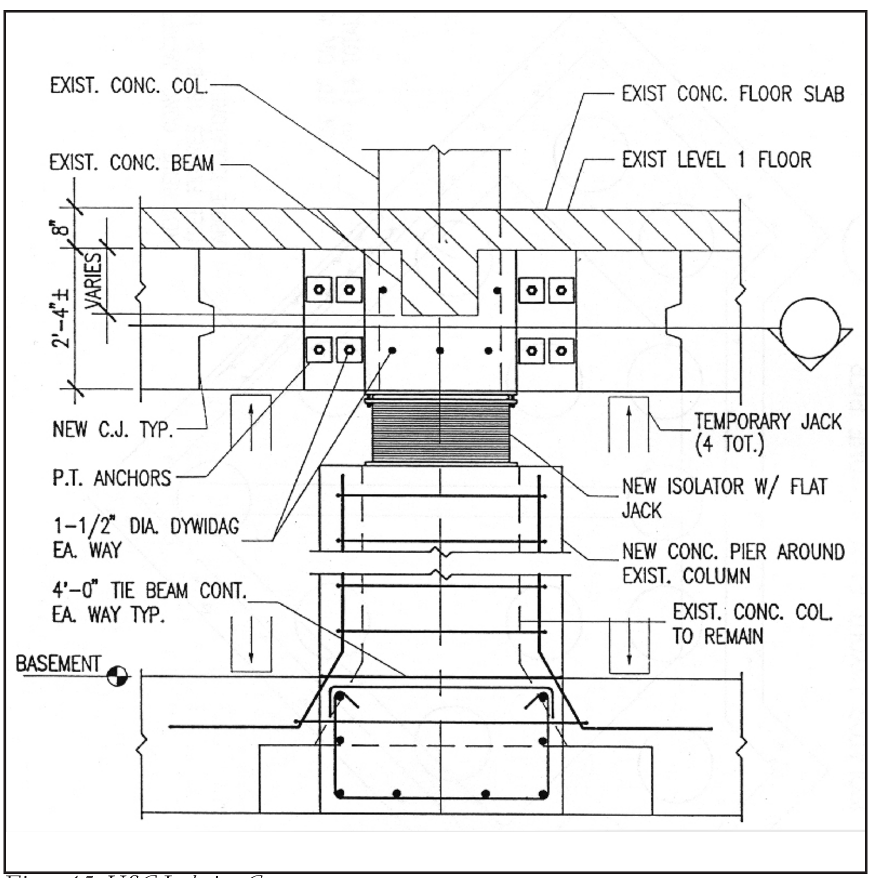
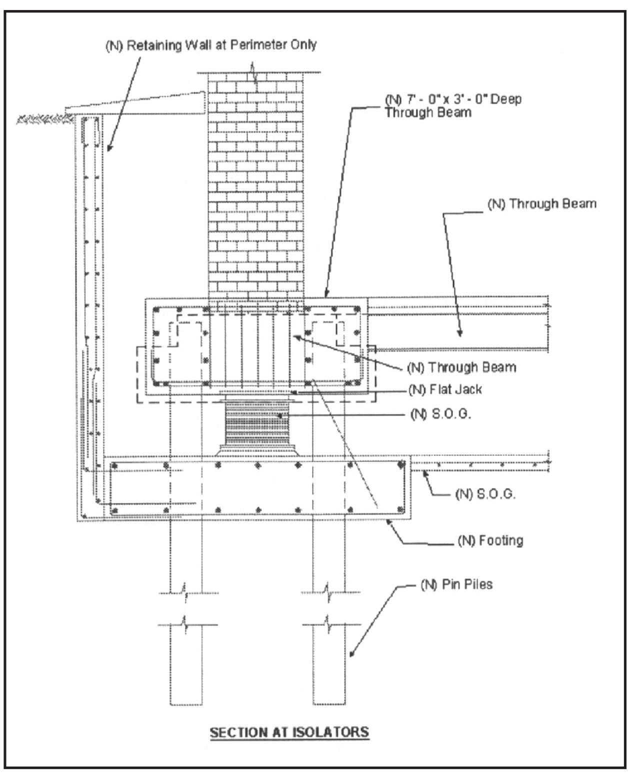


Figure 15 USC Isolation Concept

Old Courthouse St. Louis, Missouri

Figure 16 Old Courthouse - St. Louis

A base isolation retrofit study of the Old Courthouse (OC) in Saint Louis, Missouri was conducted in 1998 as part Of "Case study Evaluation of NEHRP Guidelines for the Seismic Rehabilitation of Buildings (FEMA 273). The study confirmed feasibility of base isolation of this historic URM building, and its effectiveness in reducing the seismic demand to tolerable levels for this massive domed structure. The OC was built as a Federal courthouse in the 1830's. The building is recognized as a National Historic Landmark and is currently used as a Federal Museum. The building includes 4 wings, each including a basement, built around a central rotunda. The footprint is 228 feet x 257 feet. The rotunda is 63 feet in diameter and rises 185 feet above ground (Figure 16). The building structure is massive URM, with wall thicknesses ranging from 18" to 60". The cylindrical dome drum structure is also URM, while the dome itself consists of a light weight system of trussed iron ribs. The existing building relies on the brittle URM for its seismic resistance.



The estimated seismic forces in a major event far exceed the capacity of the existing structural elements. The initially stiff, and subsequently degrading nature of the URM makes it difficult if not impossible to come up with a technically and economically viable fixed base retrofit solution. Base isolation offers the advantage of reducing the seismic response of the building and the dome, as well as protecting the brittle elements by reducing the story drift, thus making it an effective retrofit solution for this building. The retrofit scheme involves installation of an isolation system at the basement level. It also includes addition of new concrete shear walls cast against existing brick walls, and some bracing at the dome level. (Figure 17) shows the isolator installation concept.

Figure 17 Old Courthouse, Isolation Concept

SUMMARY

Technical and economical feasibility of base isolation is confirmed for retrofit of historic domed structures with various structural systems and materials. Base isolation reduces the seismic response of the overall building and the dome, and alters the deformed shape of the buildings, thus reducing the demand for strengthening. The location of the isolation system at the base of the buildings can vary depending on the original historic details, site constraints relative to building movement, and architectural, functional and historic preservation requirements. While installation of base isolation in existing buildings is feasible, it requires careful consideration of construction sequence and the potential vulnerability of the building during construction.